

Proton Degradation of Light-Emitting Diodes†

A. H. Johnston, B. G. Rax, and L. E. Selva

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Introduction

The severe degradation of optocouplers in space has been shown to be mainly due to proton displacement damage in the light-emitting diodes that are used within the optocouplers [1,2]. However, a variety of LED technologies can be used in optocouplers and their sensitivity to proton displacement damage varies by about two orders of magnitude, as shown in Figure 1. Optocouplers are very simple hybrid devices, and the type of LED can be readily changed by the manufacturer with little cost impact. Many optocoupler manufacturers purchase LEDs from outside sources with little knowledge or control of the manufacturing process used for the LED, leading to the possibility of very dramatic differences in radiation response (JPL has observed such differences for one type of optocoupler that is used in a hybrid power converter).

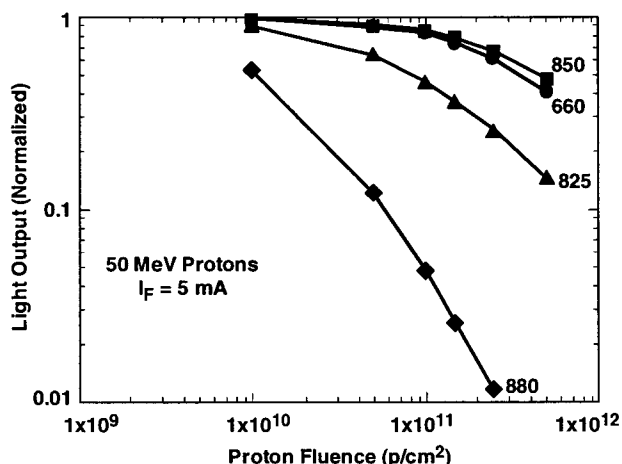


Figure 1. Degradation of LEDs of different wavelengths from 50 MeV protons

Increased understanding of LED degradation is needed not only because of their use in optocouplers, but also for basic applications of LEDs in optoelectronic systems. This paper investigates displacement damage in near-IR light-emitting diodes. Several different device types are included, as shown in Table 1. They include simple, low-cost diffused LEDs (which are amphoterically doped) as well as double-heterojunction LEDs that use multiple layers of different material types for more precise control

†The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, Code AE. Work funded by the NASA Microelectronics Space Radiation Effects Program (MSREP).

of the carrier confinement region. Although earlier work showed that amphoterically doped LEDs were sensitive to proton irradiation [3], present technology devices are considerably more degraded than the devices studied at that time.

Absolute comparison of the light output of different LED types is somewhat difficult because the high index of refraction of GaAs causes very large Fresnel losses when the device is coupled to a medium with low refractive index. The amount of light that is actually transmitted depends on physical details, including the angle over which the light is accepted and the properties of coatings and index matching materials. For this reason, most of the data in the paper is normalized to the initial light output measured by a silicon photodetector with an acceptance angle of approximately ± 20 degrees. Further details of the various LED technologies and the issue of coupled light will be provided in the complete paper.

Initial radiation tests on a small sample of devices were done for all of the LED types. More thorough testing with large sample sizes was done for two different device types from Optodiode Inc which manufactures high-reliability LEDs that are space qualified.

Table 1. LED Technologies Investigated in this Study

λ (nm)	Construction	Material	Manufacturer	
			LED	Optocoupler
880	Diffused	AlGaAs	Optodiode	- - -
880	Diffused	AlGaAs	Optek	Optek
825	Heterojunction	GaAs	unknown	Isolink
800	Heterojunction	GaAs	Optodiode	- - -
700	Heterojunction	GaAsP	HP	HP
630	Heterojunction	GaAs	unknown	Micropac

Proton testing was done at UC Davis using 50 MeV protons. Irradiations were done in steps of approximately $1-3 \times 10^{10}$ p/cm². The beam intensity was varied so that each irradiation step required about 5 minutes to complete. Devices were removed from the irradiation area after each incremental irradiation step, and tested at a number of different bias conditions, ranging from zero current to currents near the maximum operating current. A Keithley microammeter was used to measure the detector photocurrent. Each measurement sequence could be completed in less than 5 minutes. Different groups of devices were irradiated under different forward bias conditions. Some were unbiased, while others were irradiated at a fixed operating current. The highest current

used was 37.5 mA, approximately 40% of the recommended maximum current (100 mA).

Experimental Results

Comparisons of the radiation degradation of diffused and double-heterojunction devices manufactured by Optodiode are shown in Figures 2 and 3. The solid lines show mean values for unbiased devices, while the dashed lines show mean values for devices that were biased at 37.5 mA during irradiation (results for intermediate forward bias currents fell between these two limiting curves). Degradation of the OD880 (diffused technology) depended strongly on operating current. Significantly less degradation was observed for devices that were biased at high current during irradiation compared to unbiased devices or devices biased at currents of a few milliamps.

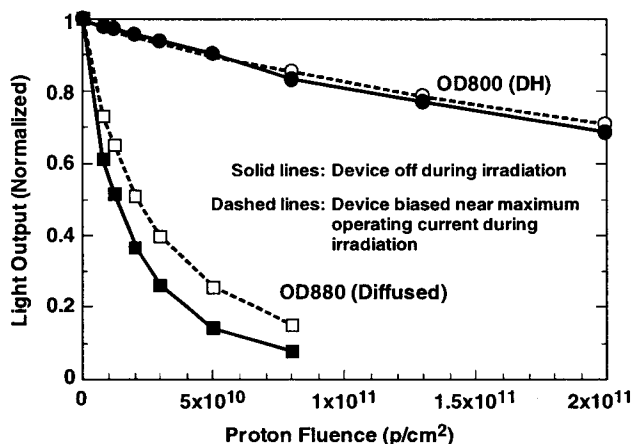


Figure 2. Degradation of two Optodiode LED technologies measured at a forward current of 1 mA.

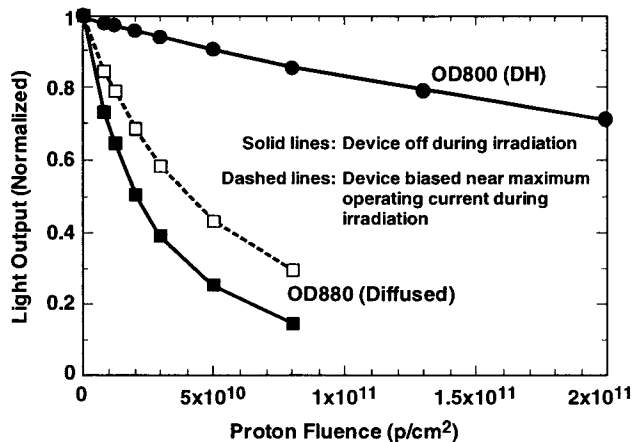


Figure 3. Degradation of two Optodiode LED technologies measured at a forward current of 37.5 mA.

In contrast, the OD800 devices exhibited little or no dependence on bias conditions during irradiation. Note also that damage in the OD800s was about the same at low and high measurement currents, whereas significantly less damage occurred in the OD880s when they were measured at high forward current.

Although it appears from these results that the 800 nm double heterojunction LEDs would be a better choice for space applications because of the lower radiation degradation, the 800 nm LEDs are much less efficient, producing only about 15% of the optical power of the 880 nm devices prior to irradiation. Thus, although the 800 nm LEDs are, on average, much less affected by radiation, their reduced light output must also be considered in device selection.

Another important issue is the uniformity of the radiation response. More than 80 of the 880 nm devices were subjected to radiation under various bias conditions, and although differences of approximately a factor of two occurred in the relative degradation of the best and worst device from the total population, none of the devices behaved in an abnormal way.

This was not the case for the other Optodiode LED technology. Two of the 800 nm devices degraded quite differently from the majority of the devices in the test sample (a total of 17 devices). An example is shown in Figure 4. Initially all devices worked satisfactorily even at very low forward currents (1 mA). However, after the first radiation level the minimum current for operation (effectively a threshold current) increased to about 10 mA for one device, and its light output was much less than that of typical devices until the forward current was increased to about 40 mA. This threshold current continued to increase at higher radiation levels, as shown in the figure. At low current the forward voltage was nearly 0.5 V lower than the preirradiation value for the abnormal device, whereas the forward voltage of devices that behaved normally changed by only a few millivolts. A second unit from the population also behaved abnormally, with similar characteristics. The extreme damage that occurred for those two parts at low currents was unaffected by operating current, and appeared to be a stable condition that did not recover after irradiation.

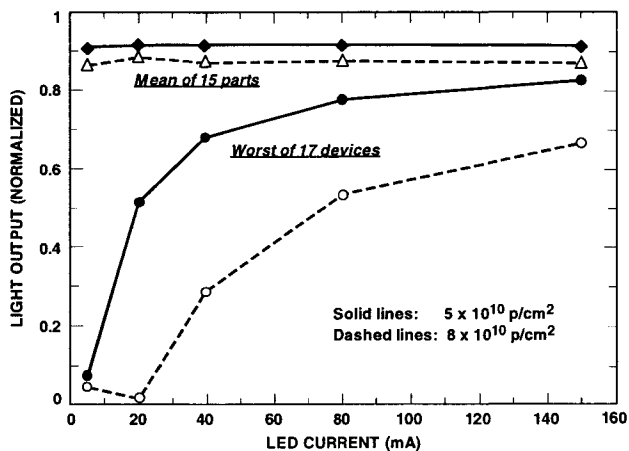


Figure 4. Dependence of normalized output power on forward current for the OD800 LED.

Current-Enhanced Annealing

Barry, et al. did annealing experiments on unbiased amphoterically doped LEDs over a two-week time interval [4]. They found that less than 5% of the damage recovered. Our measurements of amphoterically doped LEDs that remained unbiased after irradiation is consistent with their results, leading to the conclusion that little or no damage recovery occurs in unbiased devices of that type.

However, LED damage can be annealed under forward injection [3]. This was also noted by D'Ordine in studies of optocouplers [5]. We examined the effects of bias on damage in some of our devices by passing different amounts of current through irradiated devices and doing periodic measurements of the output light intensity. Recovery was much more rapid when high currents were used during the post-irradiation recovery period compared to low currents. The maximum current that was used was 50 mA, one-half the maximum rated current of the device. Approximately 1/2 of the damage recovered after several hours of operation at 50 mA, in contrast to the unbiased devices which recovered less than 1% during comparable time periods.

The effect of operating current on annealing could be analyzed by considering the total charge that flowed through the device after irradiation. Figure 5 shows how data for three different devices that were annealed under different current conditions compared from the standpoint of total charge. The recovery appears to be logarithmic with time, and begins to saturate for the device that was annealed with the largest current.

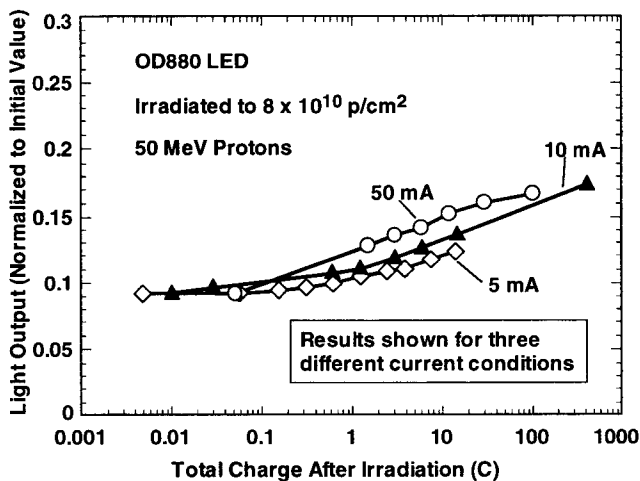


Figure 5. Normalization of current-dependent annealing to total charge.

The amount of damage that recovered during post radiation annealing is roughly the same as the difference in the degradation of devices that were irradiated at low and high currents (see Figures 2 and 3), implying that the same basic effect is involved in reducing the damage for devices that are forward biased during irradiation. The initial data on post-radiation annealing was done over a limited time period, and although the recovery appears to be on the verge of saturation, it is possible that more damage will

recover if the current flow after irradiation is extended to longer time periods.

Recommendations for Hardness Assurance

The variability in the radiation response of LEDs is made even more important by their extreme sensitivity at very low proton fluence levels. Equivalent total dose levels of 1-2 krad(Si) cause severe degradation in environments that are dominated by protons, making them among the most sensitive components. Failures of optocouplers have been observed in Earth-orbiting spacecraft such as Topex-Poseidon, and screening the more sensitive devices can be important in successfully applying them in space.

Although none of the 880 nm devices exhibited the abnormal behavior that was seen for a small number of the 800 nm LEDs, the amount of degradation of the 880 nm devices varied significantly for different units. There did not appear to be any correlation between initial light intensity and radiation sensitivity. However, there was a strong correlation between the peak light emission wavelength and radiation sensitivity, as shown in Figure 6 (the spectral width of a typical LED is about 70 nm, so the range of peak emission wavelength is much smaller than the total spectral width). Note that the worst devices degrade by nearly a factor of two at 8×10^9 p/cm², while others retain nearly 75% of their light output at the same radiation level. Thus, better control and specification of wavelength appears to be an effective way of limiting the range of radiation behavior.

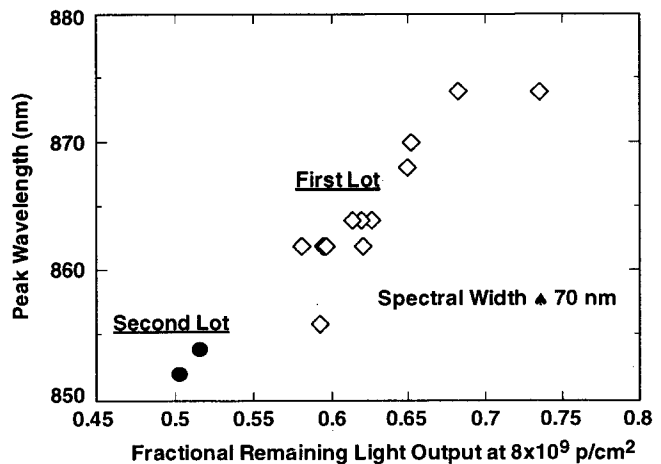


Figure 6. Correlation between degradation and wavelength for diffused LEDs

Barry et al. have shown that lifetime measurements can be used to characterize the behavior of diffused LEDs [6,7], which was also noted in the earlier work by Rose and Barnes. The lifetime of the OD880 LEDs only decreased by approximately a factor of two at the highest radiation levels in our tests, and thus lifetime measurements probably do not have the accuracy and resolution that is required to be an effective hardness tool in these samples.

There did not appear to be any correlation between wavelength and radiation sensitivity of the 800 nm double-heterojunction LEDs. However, there were significant differences in the forward voltage characteristics of the 17 different samples, and the two abnormal units required larger forward voltage at high current compared to typical devices in the sample. This suggests that preirradiation forward voltage vs. light output characteristics may be a useful screening method for those devices.

Conclusions

This paper has examined proton displacement damage in light-emitting diodes using a variety of bias conditions and a relatively large number of devices for selected technologies. Although double-heterojunction LEDs are less degraded than amphoterically doped diffused LEDs, the lower output and statistical variability of DH LEDs makes them more difficult to use in space.

Damage in diffused LEDs depends on operating conditions. It is important to characterize the dependence on bias to make sure that the experimental characterization of damage will actually correspond to circuit use conditions. Post-irradiation recovery measurements indicate that the amount of damage recovery depends on the total charge that passes through the junction after irradiation, and this appears to be a promising way to characterize the dependence of damage on operating conditions.

Many changes have occurred in LED technology during the last twenty years [8], and much of the earlier work on radiation degradation has to be modified to account for changes in efficiency and processing. The final paper will include radiation results for a number of LED types and will help establish ways to select devices with better immunity to radiation damage.

References

1. B. G. Rax, et al., "Total Dose and Proton Damage in Optoisolators" IEEE Trans. Nucl. Sci., NS-43, 3167 (1996).
2. H. Lischka, et al., "Radiation Effects in Light Emitting Diodes, Photodiodes and Optocouplers," RADECS93 Proceedings, p. 226.
3. B. H. Rose and C. E. Barnes, "Proton Damage Effects on Light Emitting Diodes," J. Appl. Phys., 53(3), 1772 (1982).
4. A. L. Barry, et al., "The Energy Dependence of Lifetime Damage Constants in GaAs LEDs for 1-500 MeV Protons," IEEE Trans. Nulc. Sci., 42, 2104 (1995).
5. M. D'Ordine, "'Proton Displacement Damage in Optoisolators," 1997 Radiation Effects Workshop, p. 122.
6. M. V. O'Bryan, et al., "Single Event-Effect and Radiation Damage Results for Candidate Spacecraft Electronics," 1998 IEEE Radiation Effects Data Workshop, p. 39.
7. A. L. Barry, et al., "An Improved Displacement Damage Monitor," IEEE Trans. Nulc. Sci., 37, 1726 (1990).
8. D. Vanderwater, et al, "High-Brightness AlGaInP Light Emitting Diodes," Proc. of the IEEE, 85, No. 11, 1752 (1997).